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Abstract. Terraces cover large areas along the flanks of many alpine and prealpine valleys. Soil slips and soil slips-debris flows are recurrent phenomena along terraced slopes. These landslides cause damages to people, settlements and cultivations. This study investigates the processes related to the triggering of soil slip-debris flows in these settings, analysing those occurred in Valtellina (Central Alps, Italy) on November 2000 after heavy prolonged rainfalls. 260 landslides have been recognised, mostly along the northern valley flank. About 200 soil slips and slumps occurred in terraced areas and a third of them evolved into debris flows.

Field work allowed to recognise the settings at soil slip-debris flow source areas. Landslides affected up to 2.5 m of glacial, fluvioglacial and anthropically reworked deposits overlying metamorphic basement. Laboratory and in situ tests allowed to characterise the geotechnical and hydraulic properties of the terrains involved in the initial failure. Several stratigraphic and hydrogeologic factors have been individuated as significant in determining instabilities on terraced slopes. They are the vertical changes of physical soil properties, the presence of buried hollows where groundwater convergence occurs, the rising up of perched groundwater tables, the overflow and lateral infiltration from superficial drainage network, the runoff concentration by means of pathways and the insufficient drainage of retaining walls.

1 Introduction

In the past centuries agriculture represented the most important source of sustenance for people. In mountainous areas with favourable climate, agriculture has been intensively practised in the valleys bottom. The need of cultivable and well exposed areas determined the extensive anthropogenic terracing of a large part of the valley flanks. Landslides are a quite recurrent phenomenon in some of these settings. They are prevalently represented by soil slips, soil slumps and soil slip-debris flows (Campbell, 1975; Moser and Hohensinn, 1983; Crosta, 1990, 1998). These landslides are cause of economical losses and sometimes of casualties. They damage cultivations, settlements and pose hazard to the safety of people. Soil slip-debris flows are gravity-induced mass movements and are one of the most hazardous natural phenomena (Costa, 1984; Johnson and Rodine, 1984). Their considerable hazard potential is related to the abundance of susceptible areas, the high areal density and the high velocity of the movements. These shallow landslides in alpine, prealpine, and piedmont regions can be triggered by rainstorms of high intensity and short duration or by prolonged rainfall of moderate intensity, and by snow melting (Moser and Hohensinn, 1983; Crosta, 1998; Crosta and Frattini, 2002).

Socio-economical changes that occurred in the last 40 years caused a reduction in attention for the tillage and maintenance of terraced slopes and, in some cases, their abandoning. The lack of maintenance is only one of the possible causes involved in slope failures. The aim of this paper is to analyse the processes involved in shallow landslide triggering on terraced slopes. This study has been conducted considering the landslide event that affected Valtellina (Central Alps, Northern Italy) on 14–17 November 2000 (Fig. 1). A prolonged and intense rainfall event triggered 260 shallow landslides on an area of 270 km^2, most of them occurring on terraced slopes. This area suffered other intense landsliding phenomena on 1983 and 1987 (Cancelli and Nova, 1985; Crosta, 1990; Polloni et al., 1991; Guzzetti et al., 1992). On May 1983 a severe meteorological event triggered more than 200 shallow landslides, with a failure density of 60 landslides per km^2, causing 17 casualties in Tresenda. The July 1987 event claimed 12 lives and triggered several hundreds of soil slips (Crosta, 1990).

In order to determine the processes and mechanisms that triggered landslides, accurate field observations concerning morphological, stratigraphical and hydrological settings have been conducted at the source areas of several tens of landslides. Disturbed and undisturbed soil samples were col-

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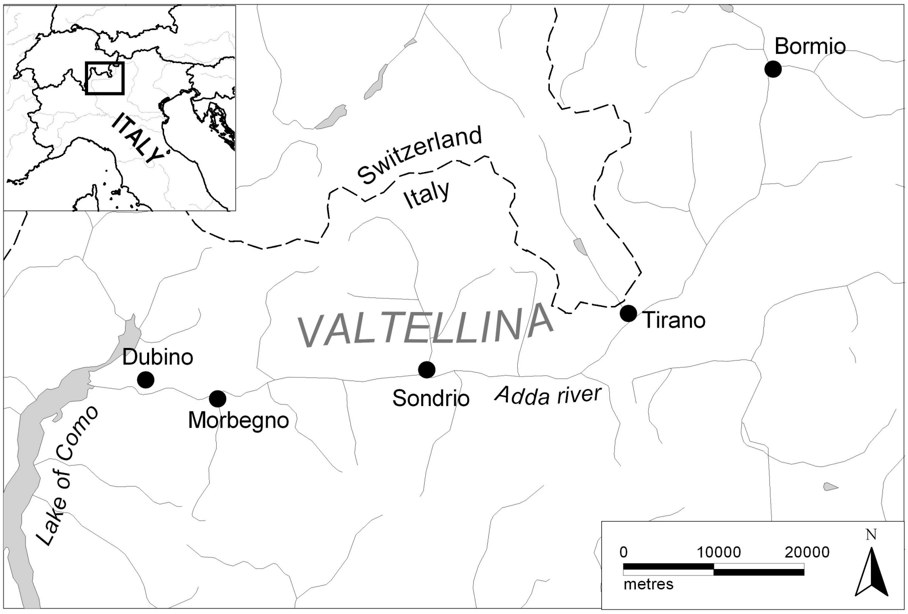


Fig. 1. Location map of the study area in Valtellina (Lombardy, northern Italy).

lected at the source areas along the failure surfaces. These samples have been analysed in order to determine physical and mechanical characteristics of soils. Additional data about soil properties involved in landslides came from in situ permeability tests. The choice of the examined source areas was influenced by accessibility, exposure and degree of disturbance or integrity of the failure surface.

2 Geological settings

Valtellina is an E-W trending valley located in Central Italian Alps (Fig. 1). The valley is superimposed on a regional fault, the Insubric line, dividing Southalpine units from Austroalpine and Penninic units. The bedrock is mainly composed of metamorphic (gneiss, micaschist, phyllite and quartzite) and intrusive rock units, with subordinate sedimentary rocks. Due to the proximity of this tectonic lineament, cataclastic and mylonitic zones are present in the bedrock. Valtellina represents the upper drainage basin of the Adda river, which flows in a flat alluvial plain up to 3 km wide. Alluvial fans at the outlet of tributary valleys can reach a considerable size, with a longitudinal length up to 3 km. The elevation of the valley bottom ranges from 200 m a.s.l., where the Adda river joins the Como lake, up to 400 m. a.s.l. near Tirano, whereas valley flanks show elevations up to 3000 m a.s.l. Valtellina has a U-shaped valley profile derived from Quaternary glacial activity. The lower part of the valley flanks is covered with glacial, fluvio-glacial, and colluvial deposits of variable thickness. Terraced areas cover, prevalently on the northern valley flank, about 7% of the slopes in the study area, for a total of 17 km^2. They are retained by dry stone walls usually between 1 and 2.5 m in height, with a maximum height up to 4 m. In steeper areas with bedrock outcrops, landfill topsoil has been put in place by anthropic work. On these areas high quality vineyards and apple cultivations are implanted.

The realisation of terraces implies changes in morphological, stratigraphical, hydrological and hydrogeological settings of the slopes. The average terrain gradient of the slopes is 42°. Vertical dry stone walls retain terraces with mean terrain gradient ranging between 15° and 25°. The renewed morphology determines also variations in the subsurficial hydrology of the slopes. An artificial drainage network (named "valgelli") has been realised in order to regulate flowing water. These works locally vary in shape and arrangement. In some cases, paths are used both as passages within the different orders of terraces and as drainage structures. Stratigraphical changes are related to the reworking of deposits due to cuts and fills performed during the realisation of terraces. Usually these operations have been accomplished minimizing the volume of mobilised material in order to obtain the widest and most flatten area. In some cases the backfilling has been realised with soils taken in nearby areas. This induced strong changes in the stratigraphy of the superficial deposits and influenced the sub-superficial hydrogeology of the shallower deposit, too.

3 Landslide event

On November 2000 Valtellina suffered intense and diffused landsliding (Fig. 2). The main landslide event occurred on 17 November, causing one casualty in Dubino. Other landslides occurred also on 6 November and on 14 November of the same year. These phenomena removed portions of cultivated areas, caused the interruption of transportation corridors and the temporary evacuation of people. Field surveys allowed to map a total of 260 landslides, 146 of which are shallow soil slips or slumps and the remaining are soil slip-debris flows

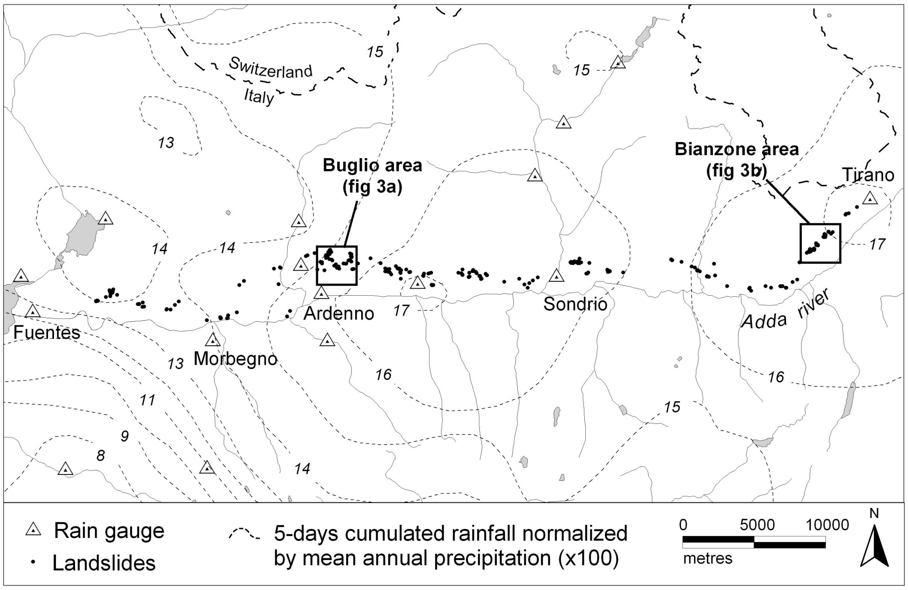


Fig. 2. Map of the study area. The landslide distribution and the maximum 5 days cumulative rainfall, normalised by mean annual precipitation, for the November 2000 event, are reported. Rain gauges considered for the interpolation of rainfall data are shown.

affecting Quaternary covers. Soil slips and slumps are characterised by small size and thickness (up to 1.5 m), with volumes up to few cubic metres.

Figures 3a and b report two landslide maps of areas with high landslide density near to Buglio in monte and Bianzone, respectively (see Fig. 2 for localisation). The maps show the localisation of the November 2000 landslides and represent the spatial distribution of historical failures, as determined by photo aerial interpretation. Landslides sometimes occurred in areas of runoff and sub-superficial flow convergence. In other cases they are associated to the reactivation of older soil slip-debris flows scars (Figs. 3 and 4).

The areal distribution of November 2000 slope failures in Valtellina is not homogeneous. Landslides on woodland or grassland has been observed only in the Lower Valtellina area, between Dubino and Sondrio. The maximum landslide density of about 4.4 landslides per square kilometre has been observed near Dubino. This value of landslide density has been computed on wooded areas up to the lower limit for snow cover (1300 m a.s.l.) on November 2000. An average landslide density of 11.5 failures per square kilometre has been determined on terraced terrain. The maximum values have been observed at Bianzone (49.0 landslides/km^2) near Tirano, and at Cino (26.8 landslides/km^2) near Dubino.

3.1 Statistical analysis and landslide size distribution

Figure 4 reports the distribution of landslides occurred on November 2000, according to the different land use. About 75% of slope failures took place on terraced areas, and are mostly represented by soil slips and slumps. The prevailing landslide typology observed in woodland is soil slip-debris flows, with instabilities affecting Quaternary deposits up to 4 m. The total number of soil-slip-debris flows (grey to black filling in Fig. 4), including those occurred in hollows and at old slide scars, is similar. The number of soil slips and slumps is ten time greater in terraced areas than in woodland. This is both due to the possible incompleteness of the inventory, because of thick vegetational cover and unfavorable slope exposure, and to the anthropogenic disturbance in terraced areas. Old soil slip-debris flow scars have been identified by aerial photo interpretation but they could have been obliterated by anthropogenic activity to restore terraces.

Frequency area statistics gives more information about the data base completeness and landslide event characteristics (Hovius et al., 1997; Malamud and Turcotte, 1999; Reichenbach et al., 2002). Both cumulative and non cumulative statistics have been applied to the data set. The cumulative percentages – size distribution for terraced and woodland areas are plotted in a log-log graph (Fig. 5a). The curves can be fitted by a power law function ($cf = c \times A^{-\alpha}$) for landslide areas ($A$) greater than 3.8×10^{-5} km^2 and 1.05×10^{-3} km^2 for terraced areas and woodland areas, respectively. The exponent, α, of the power law functions ranges between 0.84 and 0.89, but the coefficient, c, is 5 times greater for the curve fitting frequency – size on woodland. This derives from the greater relative number of large landslides on woodland. The cumulative frequency – size distribution could be restrictive and misleading (Pelletier et al., 1997). For this reason non cumulative statistics has also been applied. The derivative of the cumulative number (N_C) of landslides with area greater or equal to a value (A), is plotted as a function of the landslide area (A) for the two data sets in Fig. 5b. The most frequent landslide size for terraced areas is indicated by the rollover position. It occurs at about 7×10^{-5} km^2, and the curve is fitted by a power law relation ($-dN/dA = b\times A^{-\beta}$) for areas greater than 7×10^{-5} km^2, with an exponent, β, of 1.85 and a coefficient, b, of 0.03. The exponent is below the minimum range indicated by Guzzetti et al. (2002) on the base of world-wide landslide inventories. The curve for the

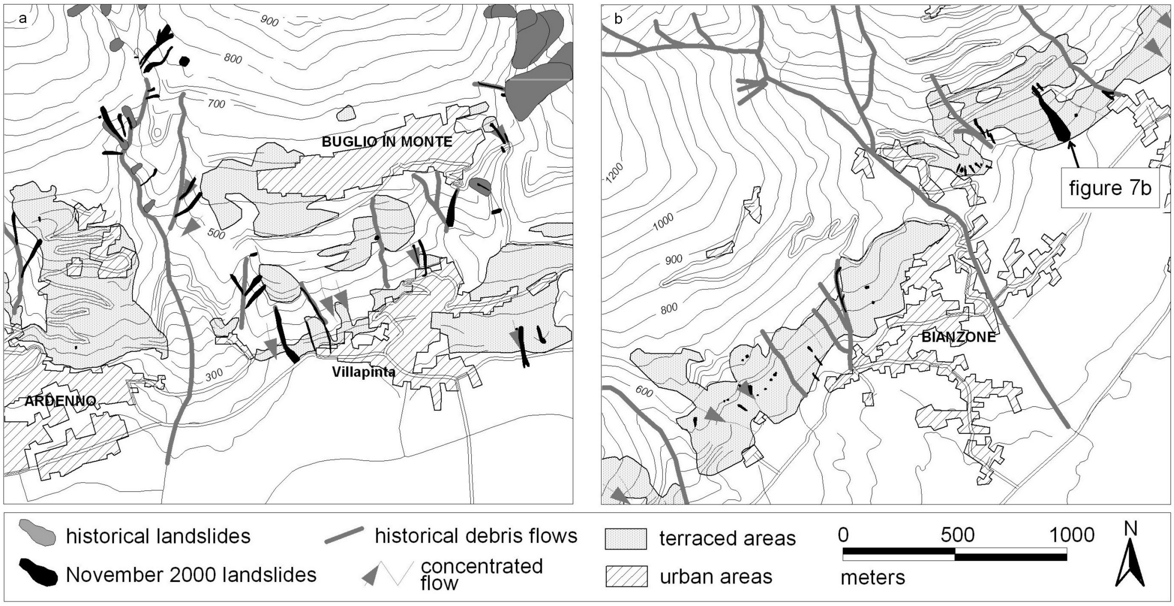


Fig. 3. **(a)** Landslide maps for the Buglio area. **(b)** Landslide map for the Bianzone area. See Fig. 2 for localisation of the two areas. Historical landslides and those occurred during November 2000 are reported together with extension of terraced areas.

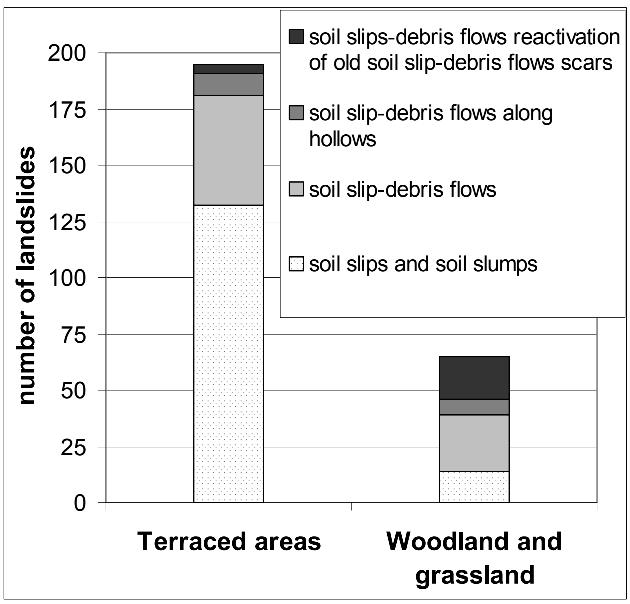


Fig. 4. Number of mapped landslides in the terraced and woodland settings for the November 2000 event. Four different landslide types are considered in two main settings (terraced and woodland areas).

woodland and grassland areas shows some interesting features. It does not show a rollover, moreover the tail of the curve is fitted by a power law curve for $A > 1.6 \times 10^3$ km^2, with a negative exponent of 1.85 and a coefficient b of 0.07. We retain that the landslide data set for woodland and grassland is probably incomplete, with a great underestimation in the small to medium landslide size range. The tail of the curve is certainly the most complete part of the inventory over the whole data set and it can be considered as representative of the whole distribution. We observe the parallelism of the two fitting lines. It suggests a similarity in landslide distribution on terraced and on woodland and grassland settings. The areas under the frequency – area distributions represent the relative total landslide areas for each data set. Therefore, the woodland and grassland areas seem characterised by a larger landslide area with respect to terraced areas.

3.2 Debris flow runout analysis

The morphometric and morphologic characteristics of debris flows in the two settings can be compared. Source areas of debris flows on terraced areas are characterised by a modal width of 8 m, but scars up to 20 m wide have been mapped. The thickness of Quaternary deposits at source areas range from 0.5 m to 2.5 m. The profile of the failure surface at source areas varies from curvilinear or almost straight to undulated and it suggests a retrogressive distribution of activity. Mean slope angle of the failure surface at source areas is 44°. The sliding material did not always mobilise completely by flowing downslope. Debris flows travelled from a few metres up to more than 600 m, with differences in elevations (i.e. fall height) up to 230 m. The frequency distributions of the total length of soil slip-debris flows on terraced and on woodland or grassland areas are compared in Fig. 6a. In the latter settings, the total debris flow lengths measured are about 3.5 times greater than those occurred on terraced areas, with elevation differences up to 700 m. The striking difference in total length and elevation can be explained with the

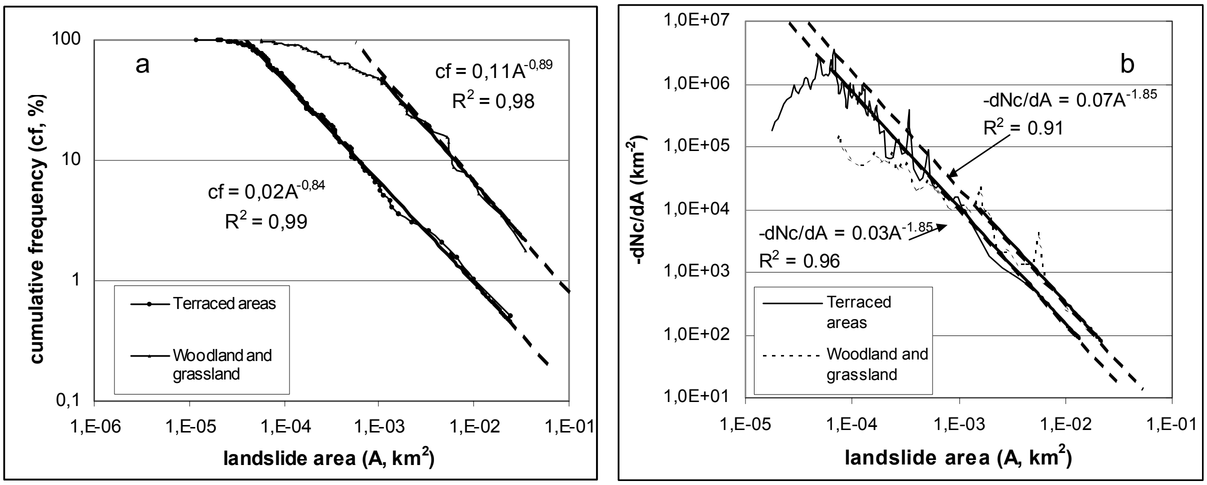


Fig. 5. Landslide total area (source, transportation and deposition) statistics in two different settings (terraced and woodland areas) for the November 2000 event. Solid lines represents the regression lines, dotted lines their extension. **(a)** Log-Log plot of the cumulative percentage of landslides, cf, with area greater or equal to the value A; the fitting is performed according to the ($cf = c \times A^{-\alpha}$) relationship; **(b)** non cumulative statistics: the derivative of the cumulative number (N_C) of landslides with area greater or equal to the value A is plotted as a function of the landslide area (A); the fitting is performed according to the ($-dNc/dA = b \times A^{-\beta}$) relationship.

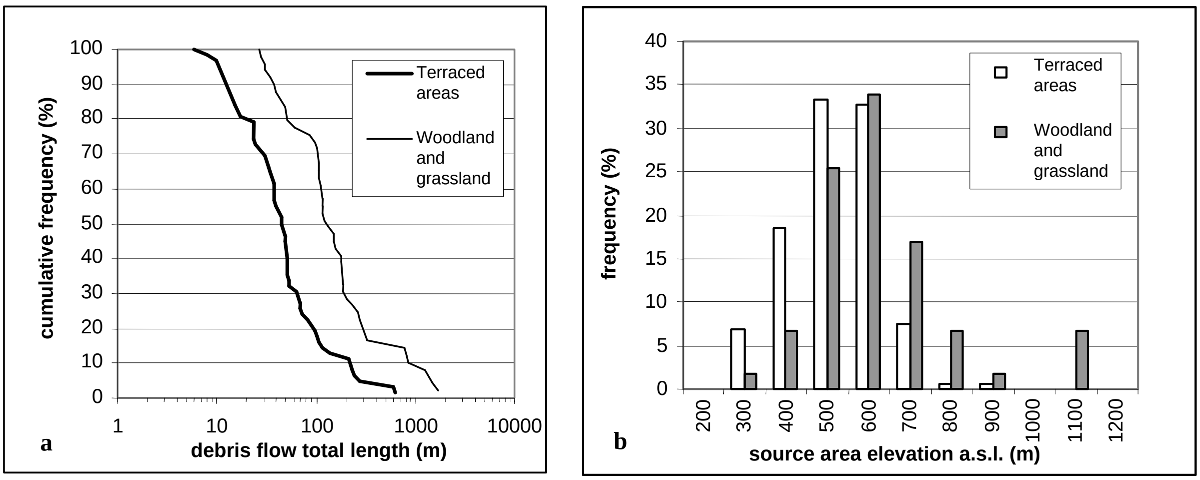
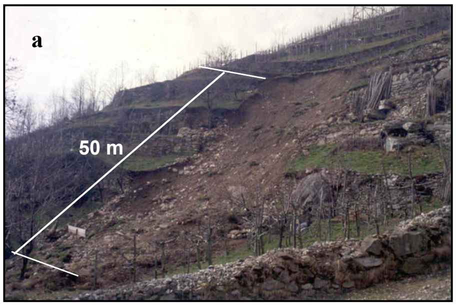


Fig. 6. Analysis of debris flows total length and location of source areas on woodland and on terraced slopes. **(a)** Cumulative frequency of debris flows total length; **(b)** source area elevation frequency.

distribution of land use along the slopes, and with the different geomorphological settings. Terraces have been realised prevalently in the lower part of the slopes and so they are located at a lower mean elevation than woodland (Fig. 6b).

Moreover, the presence of sub-horizontal steps along terraced slopes enhances the energy loss of debris flows. This is suggested by the accumulations observed in the field in correspondence of terrace steps. Nevertheless, an important factor governing the downslope debris flow evolution is the consistence of water supply at source areas. Debris flows are confined laterally where natural channels are present; otherwise they progressively increase in width along the slopes, up to 65 m. As a consequence, small initial slides (Fig. 7a) can affect wide portions of the slopes (Fig. 7b). The ratio between total fall height, H, and total length, L, travelled by soil slip-debris flows ranges between 0.3 and 0.8. Debris flows on terraced terrains usually involved volumes ranging from few tens of cubic metres up to some thousands of cubic metres. A rough estimation of total volume has been accomplished for some of the mapped landslides. These data have been compared with the empirical relationship proposed by Rickenmann (1999) for the evaluation of total travel distance of debris flows. Rickenmann showed the existence for debris flows of a dependence among travel distance L, landslide volume V and fall height (elevation difference), H, according to the following relationship:

$$L = 1.9 \times V^{0.16} \times H^{0.83}. \quad (1)$$



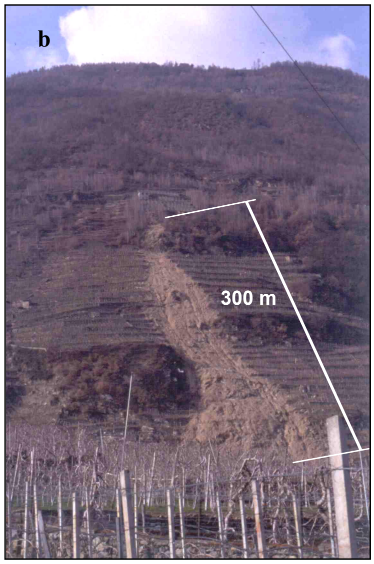


Fig. 7. Landslides on terraced areas. **(a)** Soil slip evolved in a small debris flow (about 50 m length) along a terraced slope; **(b)** the widening (up to 60 m) of an initial small soil slip (10 m wide) is shown (total length about 300 m).

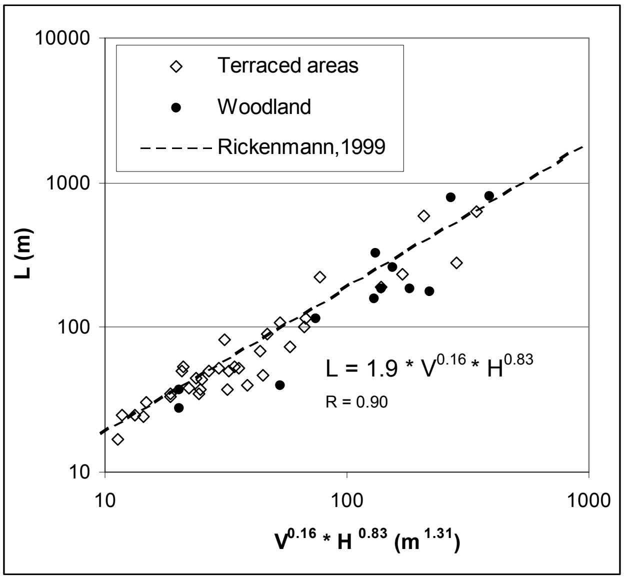


Fig. 8. Relationship among landslide total length (L), fall height (H) and volume (V) for the November 2000 soil slips-debris flows. Two landslide groups are used according to the different settings (terraced and woodland areas). Dashed line shows the empirical relationship proposed by Rickenmann (1999). The regression coefficient, R, has been determined considering the whole data. The exponent for the measure unit on the abscissas axis derives from Rickenmann analysis.

This empirical correlation points out that the elevation difference has a greater influence on total travel length of landslides than volume, which is usually more difficult to be predicted. The proposed empirical relationship fits the field data both for terraced areas and for woodland (Fig. 8).

Debris flows partially or totally destroyed retaining walls along their downslope path, eroding the superficial deposits and scraping off the vegetation. Usually the depth of erosion is limited to few decimetres, but values up 2.5 m have been measured. Deepening and washing out of materials along the axial part of landslides have been induced by superficial runoff or from water flowing from temporary springs located at source areas. Levees of some decimetres in height of unsorted material are present along the flow paths. Debris flows accumulation occurred on less steep reaches along the slopes, as morphologic terraces or roads, or at their foot, where the terrain gradient is less than 10°.

3.3 Rainfall data

Landslides occurred after a prolonged rainfall period. The total rainfall measured from 21 September to 17 November at the Sondrio rain gauge was 581 mm. This value is three times the 30 years-averaged rainfall for the same period (166 mm). From the beginning of November to the main landslide event on 17 November, 170 mm to 370 mm of rainfall were recorded at several rain gauges in Valtellina (Fig. 9). A maximum monthly rainfall of 470 mm was recorded at Ardenno. For this rain gauge the cumulative daily rainfall recorded on May 1983 and July 1987 is compared with the November 2000 data.

The main rainstorm recorded at the Sondrio rain gauge started at 23:00 LT on 12 November and lasted till 21:00 LT of 14 November. After few hours of low intensity rainfall, a new rain burst occurred between 11.00 LT on 16 November to 12.00 LT on 18 November.

Statistical analysis of rainfall data for the Sondrio station shows that the return time for the rainstorm spans from less than 5 years for 1-day rainfall values up to 20 years for the 5-

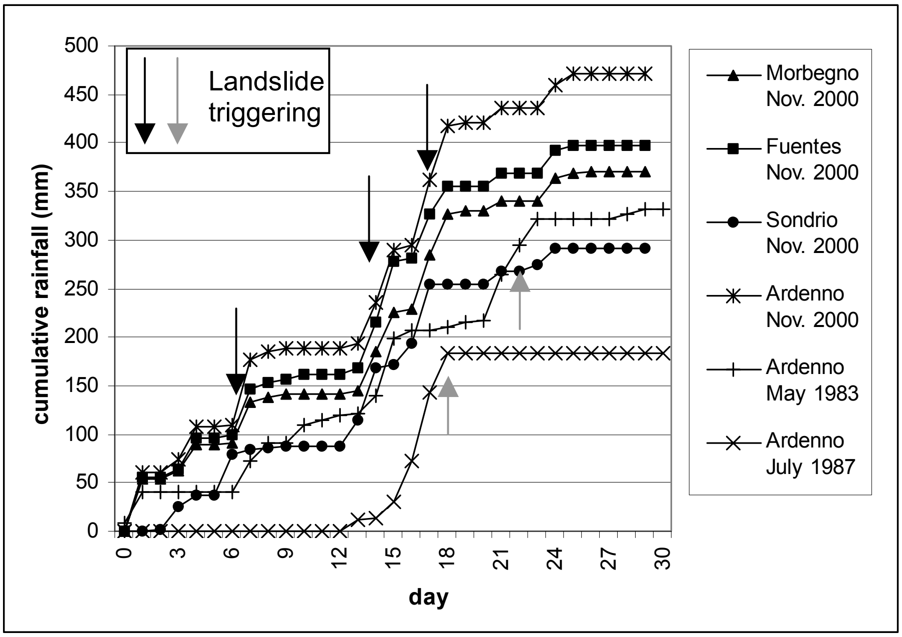


Fig. 9. Daily cumulative rainfall at 4 different rain gauges (see Fig. 2 for localisation). Data for the Ardenno rain gauge are reported for three different landsliding events (May 1983, July 1987, November 2000). Black arrows point out landslide occurrence on November 2000, whereas grey arrows show landslide triggering on May 1983 and on July 1987.

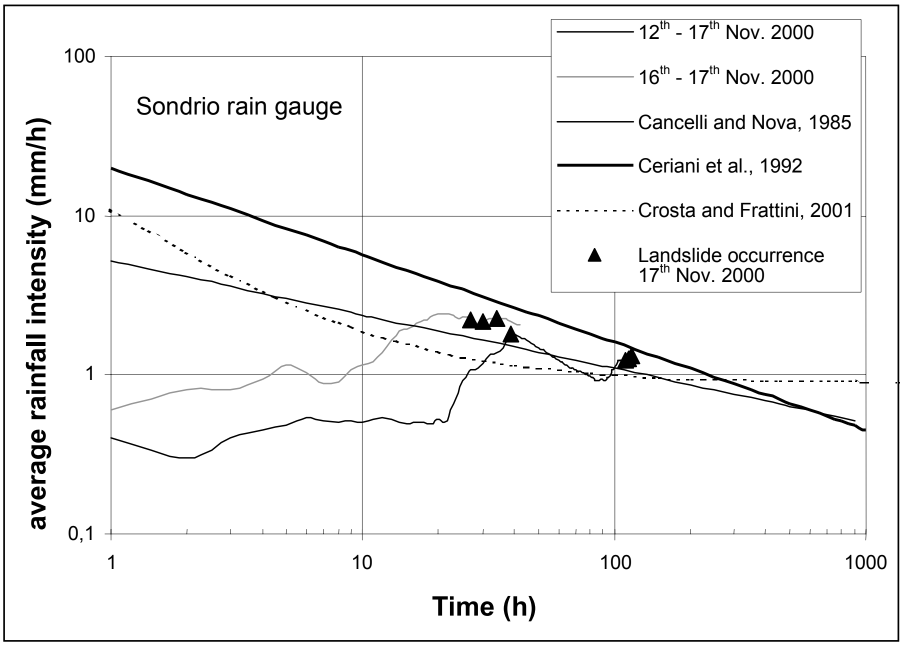


Fig. 10. Rain paths for the 12 to 17 November time interval and for the 16 to 17 November rainfall as recorded at the Sondrio rain gauge. Data are compared with existing rainfall thresholds compiled for shallow landslides in Alpine and Prealpine areas.

day cumulated rainfall (13–17 November). The contour lines showing the cumulative 5-days rainfall, normalized by the mean annual precipitation, are reported in Fig. 2. Hourly intensities were not exceptional, with return periods lower than 5 years. Maximum hourly intensity of 6.8 mm/h has been registered one hour before landslide occurrence (13:00 LT) on 14 November. From these data, we can conclude that landslides have been triggered by prolonged rainfall with low hourly intensity and with high antecedent rainfall. The rain path for the Sondrio rain gauge is reported in the intensity vs. duration plot (Fig. 10). These data are compared with existing rainfall thresholds for the triggering of shallow landslide in alpine and prealpine settings. Landslide triggering is well described by the Cancelli and Nova (1985) threshold whereas the threshold proposed by Ceriani et al. (1992) requires higher rainfall intensities. Rainfall intensities that triggered landslides lie in the long heavy rainfall field proposed by Moser and Hohensinn (1983) and above the threshold found by Crosta and Frattini (2002) by analysing worldwide data.

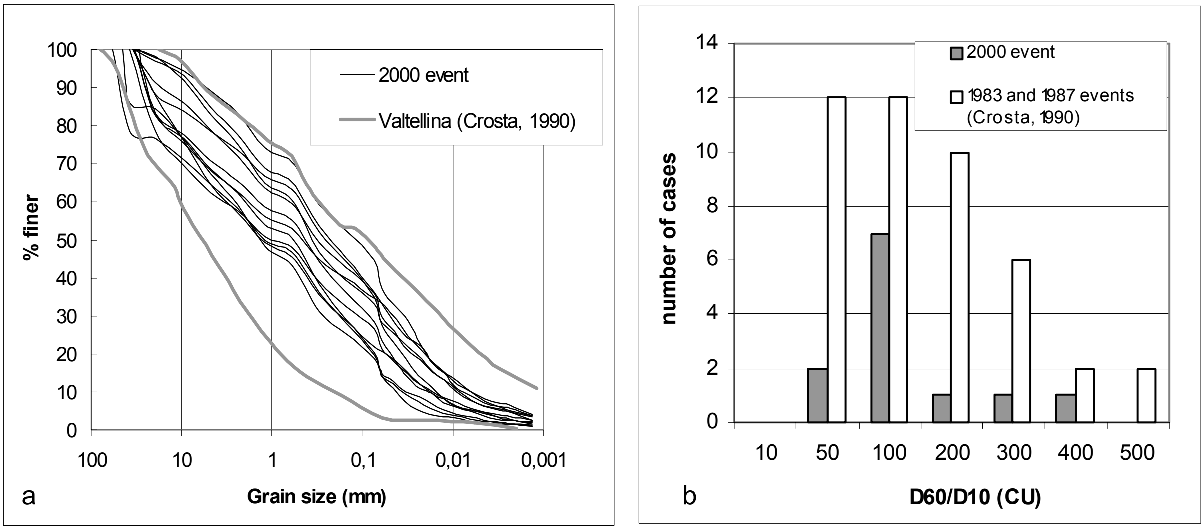


Fig. 11. **(a)** Grain size analyses for soils from source areas of soil slip-debris flows. Thick grey lines represent the grain size envelopes determined for other soils which originated soil slip-debris flow in Valtellina (1983 and 1987 events; Crosta, 1990), **(b)** frequency distribution of the coefficient of uniformity (D_{60}/D_{10}) for soils originating soil slip-debris flows on years 1983 and 1987 compared with those for November 2000.

4 Geotechnical characterisation

In situ investigations allowed to reconstruct the stratigraphical settings at landslide source areas. Slope failures occurred in glacial, fluvioglacial, colluvial and anthropically reworked deposits. In most cases failure surfaces are localised at the boundary between horizons with different physical characteristics. Disturbed soil samples have been collected at landslide source areas both above and below the slide surface. These samples should represent the variability in the stratigraphical and physical characteristics observed in the field. Laboratory tests have been performed on these samples to determine physical and mechanical properties.

The results of grain size analyses performed on collected samples (Fig. 11a) have been compared with those performed on samples taken at source areas of debris flow previously occurred in Valtellina (1983 and 1987 events, Cancelli and Nova, 1985; Crosta, 1990). The soils are similar to colluvial and glacial materials involved in the 1983 and 1987 slope failures. According to the Unified Soil Classification System (USCS) the most common type of soil is silty sand with gravel (SM). Clay content is very low, ranging between 1% and 6%. The coarser soil fraction is represented by subangular to sub-rounded crystalline cobbles. Boulders up to 50 cm in diameter have been observed in the coarser soil layers. The D_{10} ranges between 0.006 mm and 0.04 mm, with unimodal distribution, whereas D_{60} ranges between 0.3 mm and 3.9 mm. All the soils are poorly sorted, with a D_{60}/D_{10} ratio (coefficient of uniformity, CU) greater than 10 (Fig. 11b) and similar to those of the soils involved in previous events (Crosta, 1990).

Soils are usually not plastic and with a low liquid limit (LL) ranging between 16.3% and 23.9%. This suggests that small amounts of water can lead the soils to their liquid state. This characteristic, coupled with the low clay content (Ellen and Fleming, 1987), facilitate the transformation of soil slips into rapidly moving debris flows. Laboratory analyses show that in most cases there is an increase with depth of the grain

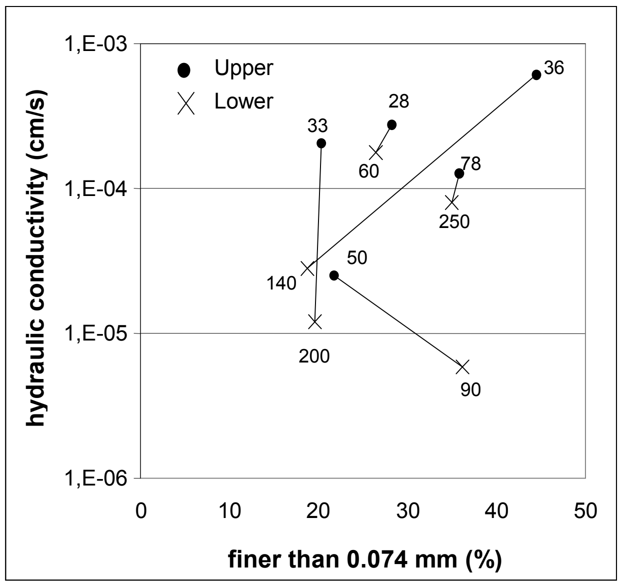


Fig. 12. Values of the hydraulic conductivity, as measured above and below the failure surfaces by the Guelph permeameter. Values are plotted with respect to the percentage of fines (less than 0.074 mm). Dots and crosses correspond to soils placed above and below the slide surface, respectively. Numbers in the plot indicate the depth in centimetres at which the permeability tests have been performed.

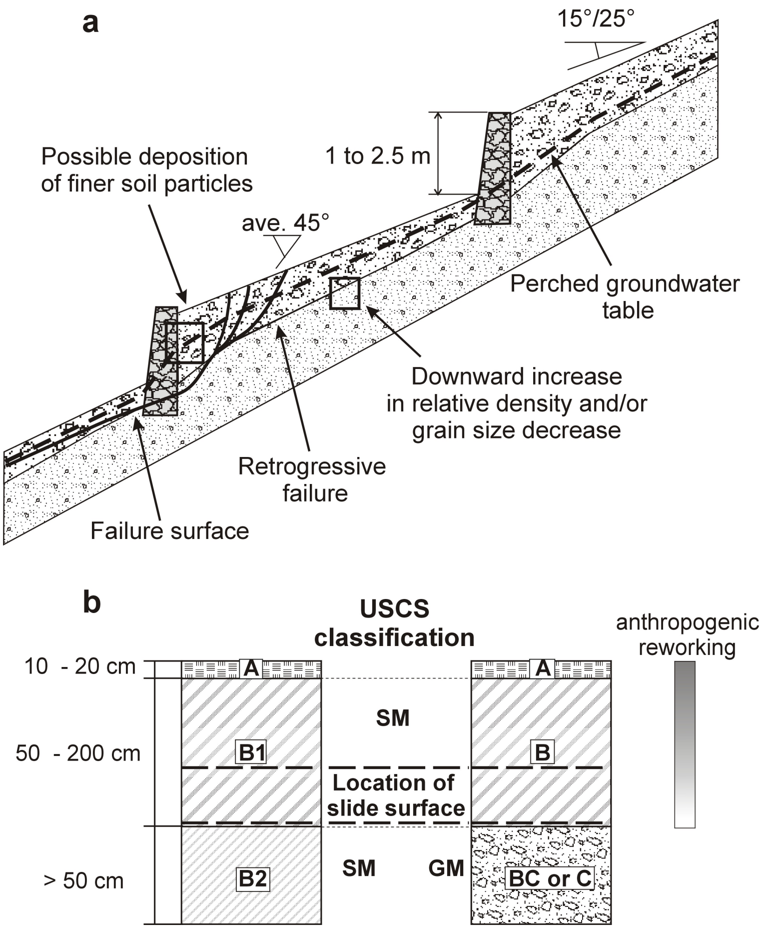


Fig. 13. **(a)** Sketched cross section along an idealized terraced area. Typical geometrical and stratigraphical settings are reported together with slope failures surfaces showing a retrogressive process; **(b)** representative stratigraphic profiles at landslide source areas with classification according to the terminology adopted for soil layers and genetic soil horizons (*A* and *B* horizons are mineral horizons, with all or many of the original deposit structure and characteristics having been obliterated, *C* horizons are the soil's parent material) and Unified Soil Classification System (USCS; SM: silty sand, GM: silty gravel). The degree of anthropogenic reworking is also shown.

size of soils, whereas no clear correlation exists between the variation of liquid limits with depth.

Direct shear tests have been performed on four remoulded samples (material finer than 2 mm) coming from soil layers lying just above the failure surfaces. The results are homogeneous, with a peak friction angle, ϕ', ranging between 34° and 35° and no cohesion. Results of laboratory tests are in good agreement with those reported in previous studies for soils involved in soil slips and debris flows in Valtellina (Cancelli and Nova, 1985; Crosta, 1990; Polloni et al., 1991).

Earlier studies on the triggering of soil slips recognised the role played by permeability barriers between the soils and the underlying bedrock (Campbell, 1975). This model is inappropriate in this case because bedrock was exposed at source areas in very few cases. Successive studies pointed out that also spatial variability of the hydraulic conductivity of soils, both vertical and longitudinal, can determine localised increase in pore pressure (e.g. Johnson and Sitar, 1990; Reid et al., 1988). We investigated the vertical variations of hydraulic conductivity at the scar areas with in situ tests. A Guelph constant head permeameter was used. The measured hydraulic conductivity of soils ranges between 6×10^{-6} cm/s and 1.5×10^{-3} cm/s. The variation of hydraulic conductivity through the slide surface has been compared with the variation of the percentage of fines (<0.075 mm). These are plotted in Fig. 12. A general decrease of hydraulic conductivity below the failure surface is evident. The lowest value computed for the ratio between hydraulic conductivities, above and below the failure surface, is equal to 1.5. The decrease in hydraulic conductivity is frequently associated to a decrease in the content of fines. This apparent contradiction can be explained with the higher compaction widely observed for the horizons underlying the failure surface. The relative degree of compaction of soil horizons has been qualitatively estimated by the resistance opposed to digging. These horizons with a greater relative density are typically glacial deposits.

5 Discussion

Dry stone retaining walls are deformable structures which require periodical maintenance in order to guarantee their mechanical and draining efficiency. The lack of maintenance of retaining walls plays an important role in the occurrence of small slides and slumps on terraced areas, but other processes are involved.

Stratigraphic settings at source areas are an important factor. More than one soil horizon is usually evident at landslide scar sites. The failure surface is located in most cases at the contact between layers with contrasting physical-mechanical

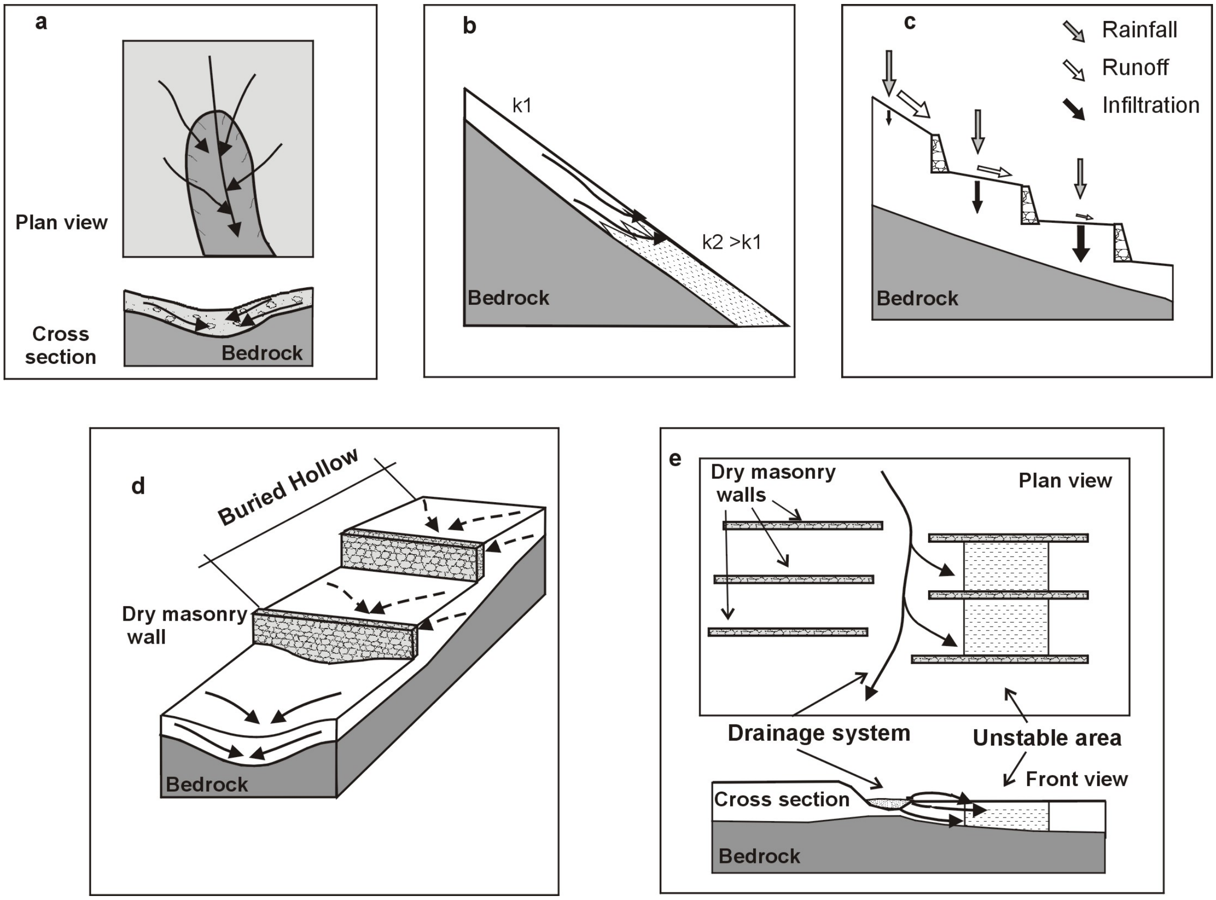


Fig. 14. Hydrological conditions related to shallow landslides triggering; **(a)** superficial and subsurface flow convergence in hollows; **(b)** downward decrease of permeability determining flow mounding; **(c)** increase of infiltration along flatter areas; **(d)** buried hollows inducing hidden flow convergence; **(e)** runoff concentration due to malfunctioning of drainage systems or to the occurrence of lateral losses of water from drainage system. c, d and e are typical conditions in terraced settings.

properties, as confirmed by laboratory and field tests. In situ permeability tests show a general decrease of hydraulic conductivity with depth, related to compaction, relative density and grain size changes. This setting allows the formation of perched groundwater tables and the build-up of positive pore pressures in the layers above the permeability barriers, which can lead to their collapse (Fig. 13a). Typical stratigraphic settings of terraced areas are represented by upper loose horizons with varying degree of anthropogenic reworking lying on compacted glacial or fluvioglacial deposits or on colluvial deposits (Fig. 13b). It can be hypothesised that the presence of deeper and more compacted horizons influenced the depth of the foundations chosen for construction of dry retaining walls. Complex stratigraphical settings are evident at some scar sites. They are related to the natural spatial variability of soils and to the repeated sequence of reworking that the upper horizons suffered during the realisation and modifications of terraces. If perched water table conditions occur in these settings, little longitudinal reduction of hydraulic permeability along the flow can promote the mounding of the water table, enhancing instability, as stated by Reid et al. (1988).

The occurrence of landslides cannot be explained by taking into account only the stratigraphical aspects. In fact similar stratigraphical settings can be found over wide areas, but landslides took place only at specific sites. The hydrologic and hydrogeologic factors must be considered. Some months after the occurrence of landslides many source areas still showed water seeping along the horizons which acted as failure surfaces. Water convergence in hollows has been recognised as an important factor in governing water supply at landslide source areas (Fig. 14a), but other processes have been identified (Figs. 14b–e), some of which specific of terraced areas. The rising up of shallow groundwater tables was recognised as responsible for landslide triggering at few sites. For example, the longest debris flow was triggered on a very gentle slope (20°) where the presence of shallow water tables is suggested by the presence of superficial (up to 1.5 m deep) and small wells intercepting water table. These water tables can rise close to the ground level only when prolonged rainfalls occur. In many other situations throughflow convergence was related to the presence of buried hollows. In order to obtain wide rectilinear terraces, greater amounts of earthfill have been put in place in correspondence of hollows. These hidden natural drainage channels are sites of groundwater flow convergence. The presence of buried hollows in terraced areas is common and usually difficult to be recognised in absence of specific surveys. Their "existence" can be determined by evaluating the thickness of the earthfill at different locations along a terrace. In some cases this is suggested by the different height of the retaining wall or by the increase in width of the terrace when moving toward the hollow axis. The interpretation of aerial photos helps to recognise buried hollows through the identification of drainage ways. This has been done for the Lower and Middle Valtellina (from Fuentes to Tirano) and in particular for the study areas (see Fig. 3).

Terracing implies great changes in the hydrologic setting of slopes. The realisation of low gradient reaches hampers the downslope flow of runoff. This enhances the infiltration of water along terraces. Runoff concentration can occur at some specific sites in terraced areas. Drainage systems can diverge water towards portions of terraces where the low terrain gradient enhances infiltration. The so-called "valgelli" are an example represented by small channels, both artificial and natural, where surface water and small creeks flow, either permanently or temporarily. It happens that these channels can loose part of their discharging water by overflowing or infiltration, especially when intense rainfall events occur. This water will flow laterally and downslope towards the inner and more depressed sectors of the terrace. There throughflow will concentrate decreasing slope stability. Pathways in terraced areas could play a role in converging runoff in localised areas feeding infiltration processes. At a few landslide sites, on terraced areas, water was brought by badly planned or malfunctioning drainage of access roads.

A greater amount of water has been observed usually at the source areas of soil slip-debris flows than at the scars of soil slips. It suggests that great amounts of water are needed to enhance the fluidisation of the failing masses, both in the source areas and along the travel zone.

6 Conclusions

Terraced areas are a widely diffused setting along prealpine and alpine valleys. They represent the inheritance of a society which subsistence was based on agriculture. Landslides are recurrent phenomena in this setting which pose a great hazard to urbanised areas growing at the footslope. A study of the processes involved in slope failures on terraced areas has been accomplished on the basis of the landslides occurred on November 2000 in Valtellina. The influence of the stratigraphical settings of source areas with horizons with vertical contrasting properties has been recognised. Changes in grain size distribution, compactness, relative density, hydraulic permeability have been observed. Most dangerous landslides in these settings are soil slips evolving into debris flows which travel distances up to several hundred metres. These most hazardous landslides are localised where the emergence of superficial groundwater or where subsurface water flow convergence occurs. Consistent runoff convergence takes place by means of malfunctioning drainage systems or by pathways. High terrain gradients along the travel areas can provide the necessary increase of energy to sustain the flows.

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